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InAs/GaAs stacked lateral superlattices grown on vicinal GaAs (001) surfaces by molecular beam epitaxy

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Abstract. The MBE growth of strained InAs/GaAs lateral superlattices on 1° vicinal (001) GaAs substrate is reported. The superlattices are produced by depositing alternately fractional monolayers of InAs and GaAs via step flow growth. We demonstrate the growth of stacked InAs quantum wires array embedded in GaAs matrix. Vertical alignment of the InAs wires in stacked array is evidenced and attributed to stress-induced self-organization growth in lattice mismatched InAs/GaAs material system.

Introduction

Low-dimensional carrier-confined nanostructures such as quantum wires (QWR) and quantum dots (QD) are of great interest because of their importance in physics and electronics. For fabrication these structures, novel methods involving self-organization phenomena in epitaxial growth have been proposed and studied extensively. The most important technique for *direct formation of high-density QWR structures* is step flow growth of compound semiconductors on misoriented substrates [1]. The existence of a regular array of equispaced steps on vicinal planes and the precise control of the deposition kinetics and amount of material deposited, insures the growth of a lateral superlattice (LSL) [2]. In this structure, laterally (i.e. in-plane) periodic composition and band gap modulation is achieved by growing alternately fractional monolayers of constituent materials via step flow growth. The serious problem encountered is that the composition modulation is far smaller than ideal in lattice matched systems, such as Ga(Al)As or Ga(Al)Sb, although the transmission electron spectroscopy (TEM) revealed the laterally periodic ordering in the structures.

On other hand, highly strained systems can afford better lateral composition modulation due to the strain-induced self-organizing growth phenomena. Very recently, step flow growth of InAs/GaAs in-plane strained lateral superlattice on misoriented (110) InP substrate have been attempted and excellent spatial composition modulation have been evidenced [3]. In this paper we describe the MBE growth and structural features of strained InAs/GaAs laterally periodic QWR structures fabricated on misoriented (001) GaAs substrates.

1 Experimental and growth results

All structures were performed by molecular beam epitaxy (MBE) using a Riber 32P system. Careful treatment of growth chamber and all molecular sources provided fabrication of AlGaAs/GaAs 2-DEG heterostructures with high electron mobility. The substrates used were epi-ready semi-insulating (001) GaAs tilted on 1° towards the [111]A direction. This value of tilt angle must lead to the formation of a regular lattice of atomic steps with 16 nm mean terrace width. The misorientation direction is chosen to have the steps parallel to the $[1\bar{1}0]$ direction. The formation of step array during growth was monitored *in-situ* with the reflection high-energy electron diffraction (RHEED) facility. The samples were rotated during growth to improve lateral uniformity of obtained structures.

The structures attempted in this work were AlGaAs/GaAs heterostructures with QWR lattice placed near the heterointerface on GaAs side. High electron mobility 2D system was attempted as a basic structure in order to obtain direct influence of additional lateral carrier confinement, introduced by QWR lattice, on 2-DEG transport properties. The basic structure consisted of following layers, in order of growth from substrate: a 900 nm thick GaAs buffer layer, three monolayers (MLs) of AlAs, a 70 nm thick AlGaAs layer capped with a 10 nm GaAs layer. The short period AlAs/GaAs smoothing superlattice was introduced in buffer layer after the first 100 nm of GaAs have been deposited. All layers in this basic structure were intentionally undoped, except of the AlGaAs layer, which was doped by two δ–planes with sheet Si-donor concentration of about 2.5×10^{12} cm^{-2} placed at distance of 20 nm and 60 nm from the heterointerface. The substrate temperature was kept nearly 620 °C during growth. At this temperature, the RHEED pattern showing single monolayer step ordering was clearly formed and kept during deposition.

For direct formation of the QWR structure in the 2-DEG region of structure described above, we used the following growth sequence. After the buffer layer, 3ML AlAs layer and additional 20 nm thick undoped GaAs layer have been deposited, the growth process was interrupted for 120 s in order to decrease substrate temperature from 620 °C to 420 °C. One, four or ten monolayer cycles of alternate InAs and GaAs half-layer deposition was then performed on separated substrates to obtain InAs/GaAs lateral lattices with different thickness. Low temperature growth stage was completed by depositing eight monolayers of GaAs coating layer in order to weaken possible indium evaporation during growth followed hereafter. The growth rate of InAs and GaAs was about 0.1 ML/s during low temperature growth stage. After this, the growth process was interrupted ones more and substrate temperature was raised to its initial value. An additional 7 ML thick GaAs layer followed by 3 ML AlAs layer was then deposited to separate a fabricated QWR lattice from the heterointerface. The growth was completed by depositing of AlGaAs and GaAs layers. Two AlAs layers served as reference planes in TEM study. Moreover, structural quality of GaAs/AlAs interface may be indicative of heterointerface sharpness in the case of lattice matched GaAs/AlAs system (first AlAs layer) and in that of the same system strained by underlying LSL (second AlAs layer).

During growth of the 1 ML and 4 ML thick lateral structures, step ordering and step flow growth regime were kept, as indicated by RHEED oscillations, when growing InAs and GaAs alternately, and, also, when growing GaAs coating layer at low temperature. On the contrary, it was found, that the step ordering disappeared after deposition of 5 ML thick LSL layer and restored again only after deposition of GaAs coating layer. The TEM plan view image revealed an extra density of dislocations in the sample attempted for the 10 ML LSL stack. This behavior seems to indicate that the deposition of InAs stripes, thicker than 5 ML, leads to termination of the step flow growth regime. To overcome this problem, we attempted growth of a vertically stacked LSL set consisted of two 4 ML thick InAs/GaAs LSLs separated by 2 nm thick GaAs layer. In accordance with the expectations, the equilibrium step ordering was kept during entire growth and the structure produced was free of dislocations.

2 Microscopic study of stacked LSLs and discussion

In order to clarify the structural features, we characterized obtained structures by high-resolution TEM. Cross section samples are prepared using the standard mechanical polishing and ion milling methods. The cross section HRTEM image shown in Fig. 1 illustrates an example of stacked LSL structure obtained by the method described above.

Cross section view $(1\bar{1}0)$ plane is perpendicular to the (001) surface plane and electron beam is directed along surface step edges. The dark areas in the image correspond to InAs-rich regions, while the gray regions indicate a larger GaAs content. The bright line in the [110] direction relates to the 3 ML AlAs layer.

The LSL stack image exhibits well resolved contrast between the constituent LSL and GaAs layers, indicating that these components are well separated. It is clearly seen from contrast-enhanced image (b), that two separate laterally periodic structures are formed in the [110] direction across the surface steps. Lateral period of observed patterns is close related to the mean terrace width of 16 nm, although the insignificant variations of lateral period ranged from 13 nm to 17 nm were also observed.

Surprisingly, a visible contrast exists between the GaAs-rich regions in LSL plane and the GaAs layers (buffer and separating ones), indicating that the indium atoms incorporate in GaAs fraction of the LSL. Because the separating GaAs layer is well resolved in the image, the changes in contrast could not be purely explained by the indium segregation or diffusion. Moreover, the extent of the dark gray regions is limited by LSL plane, indicating that these regions are directly formed during LSL deposition. This, indeed, might occur, if migration length of the indium atoms is less compared with the mean terrace width, i.e. a fraction of the In atoms deposited on surface can not reach the step edges, thus, allowing the In nucleation on the step ledges and leading to the formation of the InGaAs alloy during GaAs fraction growth cycle. The reduced width of well contrasted InAs-rich regions also proves this situation.

The most interesting feature revealed by HRTEM study is an arrangement of stacked LSL structure. Indeed, the InAs-rich regions are not tilted inside the LSL stack and, moreover, these regions are lined up in the growth direction. Thus, we suppose that the surface step arrangement is tuned by stress induced by the InAs regions, so, the In atom nucleation events occur preferably in the InAs-rich regions minimizing misfit stress accumulation. The results obtained here demonstrate a direct evidence on a short-range correlation, when growing the Ga(In)As LSL structures.

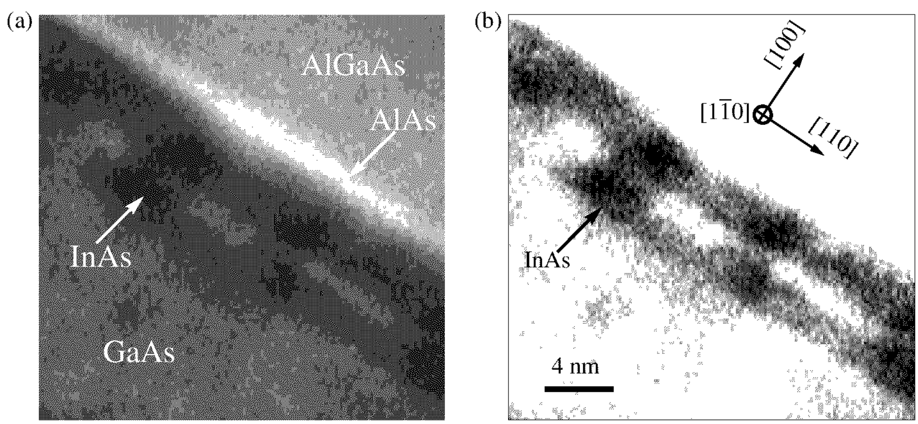

Fig. 1. Cross section HRTEM image of a stacked LSL structure, (a) shows the experimental image, while in (b) the contrast is enhanced by image processing.

3 Summary

We have shown that a modulation of the composition in two directions can be directly introduced by MBE deposition of stacked lateral superlattices via step flow growth. InAs and GaAs compounds can be combined to grow LSL on vicinal GaAs substrate, in spite of a large lattice mismatch. The HRTEM images indicated formation of laterally periodic structure with the period of the mean terrace width of the substrate used. Vertical arrangement of InAs-rich regions was obtained in stacked LSL. This feature may be attributed to the strain-induced self-organization phenomena in step flow growth mode. Close spacing of InAs quantum wires (less than 2 nm) in stacked LSL, we believe may lead to a confinement of electron gas in the InAs coupled wires.

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